The Magnetic Mechanical Analysis of Manganese Steel.

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One of the most interesting alloys for the study of its magnetic properties is manganese steel. The following paper is an attempt to correlate some of the magnetic and mechanical properties of manganese steel, in the hope that as such data are circulated it will eventually be possible to interpret from the magnetic behaviour of steel what the mechanical properties will be.

Six manganese steel rods supplied by one of the authors were drawn from the same source, 76 cm. long and 0·95 cm. in diameter, and used " as drawn." These rods were marked 1, 2, 3, 4, 5, and 6 respectively. The chemical analysis was made on rod No. 4 and showed:—

$$C \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1\text{·}25 \text{ per cent.}$$
$$Si \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 0\text{·}43 \quad \text{,,}$$
$$Mn \quad \ldots\ldots\ldots\ldots\ldots \quad 12\text{·}20 \quad \text{,,}$$

The record for the heat treatment was as follows:—" All six bars were treated at 1000° C. (five minutes), and then water-quenched in ordinary cold water. Nos. 1, 5 and 6 were then enclosed in an iron pipe welded over at the ends, and annealed. The time for cooling from 550° C. to 450° C. was about eight hours. As this treatment did not make the bars sufficiently magnetic they were again annealed at 500° C. (530° C.—475° C.) for sixty hours."

Rough tests were made on the rods (without removing outer skin) with balanced hand magnet. Rods Nos. 2, 3 and 4, were non-magnetic; hand magnet just pulled at 1/16 inch. Rods 1, 5 and 6 were magnetic; hand magnet pulled well at 3/8 inch. About 25 per cent. Sp. Mag. (S.C.I.—Swedish Charcoal Iron = 100). From these six rods Nos. 2 and 5 were selected to represent the non-magnetic and magnetic types respectively, one differing from the other only in heat treatment.

These rods were used to study the changes in length which occur when a ferro-magnetic substance is subjected to a magnetic field, as well as the effects upon the values of the intensity of magnetisation when the rods are subjected to a longitudinal stress. It would appear, therefore, that more and more is it going to be possible* to determine what will be the mechanical properties of

* Burrows, 'Sci. Paper, No. 272, Bur. Stands.'; Williams, 'Jour. Cleveland Eng. Soc.,' January, 1917; 'Topical Discussion on Magnetic Analysis, A.S.T.M.,' June Meeting, 1919: Gebert, 'Jour. A.S.T.S.,' June, 1919; Sanford and Kouwenhoven, 'Sci. Paper, No. 343, Bur. Stands.'

ferro-magnetic substances by a study of their magnetic behaviour.   In the two relations which are to be studied in this paper we have an excellent avenue of approach to this fascinating subject.

The method* devised by one of us for determining the Joule effect (length changes), was employed in this work.   The length of rods between brass extensions was 74·3 cm.   In fig. 1 is shown the variations in length of rod, No. 5, as the magnetic field was increased from zero up to nearly 3000 Gauss. This shows that for all field strengths used, the change in length was an increment.   In a similar way rod No. 2 was tried out but no changes in length could be detected, although changes as small as 0·000004 cm. could be read from the scale.

Working in the same vertical solenoid as used in the Joule effect, the rods were next tested for the effect of tension on the intensity of magnetisation (Villari effect).   In the usual ballistic method for the measurement of the intensity of magnetisation of rods a small coil of wire is wound about the middle section of the specimen and the terminals of this exploring coil attached to a ballistic galvanometer.   The rod thus equipped is placed in a long solenoid, to ensure as nearly as possible a uniform magnetic field.   The throw of the galvanometer is then observed when the current is broken and reversed in the large solenoid.   When this is done the charge flowing through the galvanometer is

$$Q = 2 \frac{\pi r_1^2 H n_1 + 4\pi I (\pi r_3^2) n_1}{R}, \tag{1}$$

where r_1 and n_1 are the radius and number of turns of wire respectively in the small exploring coil on the rod, r_3 the radius of the rod to be tested, R the resistance of the galvanometer and exploring coil circuit, H the field in the solenoid, and I the intensity of the magnetisation.

It will be seen from equation (1) that the deflection of the galvanometer depends on two main factors: the field of the solenoid and the flux induced in the rod.   If the intensity factor happens to be small and H large, it will be hard to measure I with accuracy, as the deflection of the galvanometer due to it is only a very small fraction of the total reflection.

For the so-called non-magnetic rod No. 2 it was evident that there was some magnetic induction, otherwise the hand magnet would not have pulled at any distance, no matter how small; consequently, to measure the intensity of magnetisation in rod No. 2, especial care had to be used to emphasise the intensity of magnetisation factor in equation (1).   This is accomplished in the following way: a second coil, having about twice the cross-section of

* Williams, 'Phys. Rev.,' vol. 32, p. 281, March, 1911 ; vol. 34, p. 258, April, 1912 ; 'Amer. Jour. Sci.,' vol. 36, p. 555, November, 1913.

the first exploring coil, but containing only about half as many turns, is placed over and concentric with the first exploring coil. The two coils are then connected in series with the ballistic galvanometer, so that, when the field, H, in the solenoid is varied, the E.M.F. generated in the first coil will just balance that in the second. When this is accomplished, we have the charge flowing through the galvanometer,

$$Q = 2\frac{\pi r_1^2 n_1 H - \pi r_2^2 H n_2}{R} = 0, \tag{2}$$

where r_2 and n_2 are the radius and number of turns in the outer exploring coil. If, now, the manganese steel rod is thrust through all of the coils, the charge passing through the galvanometer, when the current is broken and reversed in the main solenoid, is

$$Q = 2\frac{(\pi r_1^2 H n_1 + 4\pi I n_1 \pi r_3^2) - (\pi r_2^2 H n_2 + 4\pi I n_2 \pi r_3^2)}{R}, \tag{3}$$

whence from (2) and (3)

$$Q = \frac{8\pi^2 r_3^2 (n_1 - n_2) I}{R}, \tag{4}$$

i.e., since θ, the deflection of the galvanometer is proportional to Q, we can at once write,

$$\theta = kI. \tag{5}$$

If k can be determined, we have an absolute method* for the determination of I, which is workable when I is comparatively small. For the determination of k, the following method was employed: a long slender solenoid of radius r_4, whose general dimensions were those of the rods tested, was made up and used in place of the rods. When the current in this slim solenoid was broken and reversed, a flux was produced in the two coils connected to the galvanometer and the charge,

$$Q = \frac{2\pi r_4^2 H (n_1 - n_2)}{R}. \tag{6}$$

Here $H = 4\pi n_3 i$, where n_3 is the number of terms per centimetre in the slim solenoid, and i the current flowing through it, hence (6) becomes

$$Q = \frac{8\pi^2 r_4^2 n_3 (n_1 - n_2) i}{R}. \tag{7}$$

If we exchange the rod for the coil, and *vice versâ*, the deflections will be

$$\theta_1 : \theta = \frac{8\pi^2 r_3^2 (n_1 - n_2) I}{R} : \frac{8\pi^2 r_4^2 n_3 (n_1 - n_2) i}{R}, \tag{8}$$

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* It is to be noted that this deduction holds only for infinitely long solenoids and rods. It is assumed in this work that the ratio of length to radius is sufficiently large to make any errors due to demagnetisation effects negligible.

whence solving for I we get

$$I = \frac{\theta_1 r_4^2 n_3 i}{r_2^3}. \tag{9}$$

In making the double coil which was connected to the galvanometer, wooden spools were used, the smaller one being just the size to fit into the larger one. The inner spool was wound with 1034 turns of No. 36 silk-covered wire, while the outer one had 520 turns of No. 28, the difference in size of wire making the coils about the same length. After carefully balancing the two coils against each other, they were fastened together firmly by boiling in beeswax and allowing the wax to harden between them. For the final adjustment, a coil of some twenty turns was wound on a spool which could be rotated so as to include more or less lines of force from the main solenoid. With this small coil in series with the double coil, an exact balance between the coils could be established. The balance was tested for field strengths up to 2000 Gauss, and no observable deflection of the galvanometer was present. In all of the circuits connecting these coils, it was very necessary to keep the wires leading to and away from the coils wound together, in order to avoid induction effects as much as possible.

In determining the effects of tension on the two manganese steel rods, coils of several hundred turns were wound directly on the rods. These coils were connected to a ballistic galvanometer, and the deflections observed when the current through the main solenoid was broken and immediately reversed, first without and then with a tension of 350 kgrm. on the rod. From the ratio of the two deflections and the values of I, as determined above, the per cent. and actual change in I were calculated.

Curve 1, fig. 2, shows the values of I for corresponding values of H in rod No. 5. These values are for the rod when not under tension. Curve 2, fig. 2, is a plot of the difference between intensity of magnetisation when under tension and when relieved of it. It will be seen that, for all field strengths, so far as we were able to go, the application of a tension increased the intensity of magnetisation. This is in harmony with the results shown in fig. 1, where the change in length was an increment for all fields. If a Villari reversal point had occurred, curve 2, fig. 2, would have crossed the axis for H, and the point of intersection would be the Villari critical point for the specimen of steel under investigation.

Rod No. 2 did not show any change in intensity of magnetisation by being stretched, just as it did not show any change in length in a magnetic field. Fig. 3 shows the value of I for rod No. 2. It will be noted that I is plotted to a scale thirty-five times as great as for rod No. 5 in fig. 2. A striking similarity between the two curves is shown when they are superimposed one
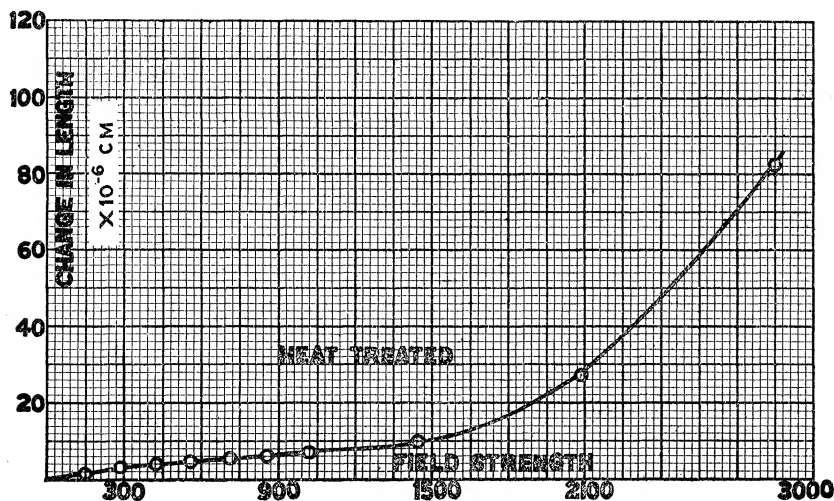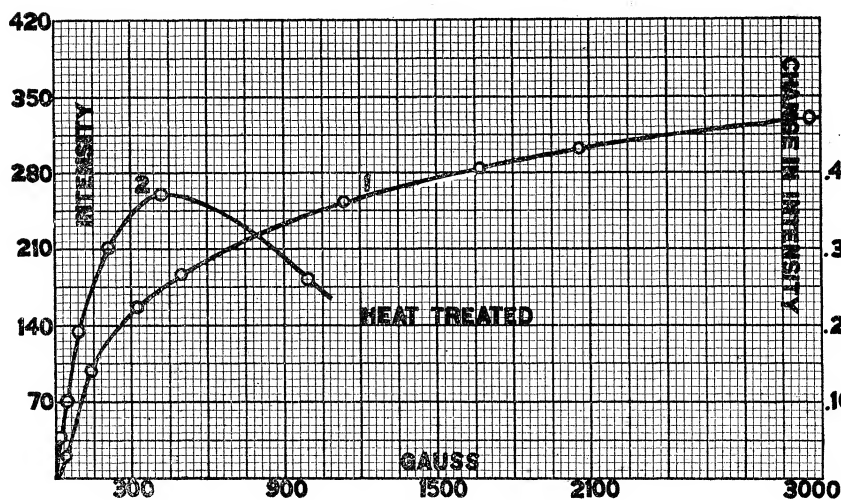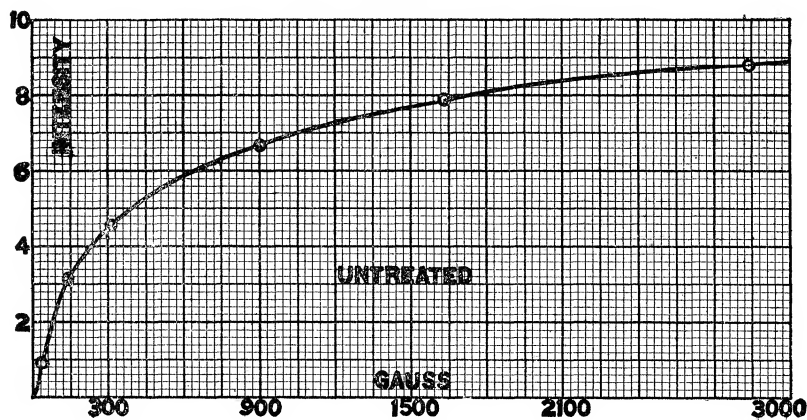
Fig. 1.

Fig. 2.

Fig. 3.

on the other.   A factor of 36 instead of 35 would have made them almost exactly coincident.

It was thought probable this might be due to slight oxidation and alteration in composition of the surface of the bar, which can only be avoided in heat treatment by observing special precautions not taken in the present instance.

As pointed out, bars Nos. 2, 3, and 4 showed a very slight attraction with the hand magnet.

It was therefore decided to remove a few thousandths of an inch from the surface of bar No. 4 by means of emery cloth.   The hand magnet was then applied to this bar, which did not show any magnetic susceptibility.   The slight magnetic qualities noticed in bar No. 2 in fig. 3 were therefore entirely due to the condition of the surface material.

It should be added here that manganese steel is very readily oxidised, and consequently bars of it, unless carefully ground, are liable to what is termed " skin " trouble, that is, slight magnetic susceptibility.   This arises from the temperatures employed in the heat treatment of this material, a very thin layer indeed being formed on the outer surface of the bar of oxidised material, which is slightly magnetic.

In the Joule phenomenon of magnetic lengthening, we have a very definite mechanical effect due to a magnetic field.   In the Villari effect, we have, as the result of a mechanical pull, a very definite change in the magnetic properties of the steel.   These are reciprocal relations, and furnish a method for magnetic-mechanical analysis.   Whether we shall ever be able to interpret all of the mechanical properties of ferromagnetic substances from their magnetic behaviour is a question, but from what has been accomplished there are fair promises, and no avenue seems more inviting than the one which has been followed in this study, where the magnetic and mechanical effects are so closely associated.   Here is a splendid opportunity for co-operation between the large steel industries with their resources of materials, and the research laboratories with their resources of skilled investigators, to make a very thorough study of this field.   X-ray methods, and the methods indicated above, seem to be about all the means we have at present to test the mechanical properties of a substance without injuring the sample tested. There are some advantages in the magnetic method.